PASSIVE STABILIZATION OF ROTATING TETHERED SPACECRAFT

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Rotating Spacecrafts can provide artificial gravity for long-term space missions, but the design of a Guidance and Control scheme for these vehicles is nuanced. For a three-segment vehicle with the propulsion element located at the center of mass, the vehicle must stabilize itself about this point even in the event of various off-nominal circumstances. Thus, a robust and passive spin stabilization system is needed. In this paper, various methods for stabilizing the system to allow for the exchange of mass and air between elements are explored and simulated.
Keywords:Dynamics

INTRODUCTION

Travel between the Earth and Mars takes many months [1] and for this to happen in safely there needs to be an improvement in the reliability of space systems during long-term, deep space missions. Some work has been done on wobble stabilization [2, 3] but while these works are similar to the topic of this paper, they don't completely cover the methods explored here. For this paper, a specific inquiry is posed: can the distribution of fluids be used to to passively stabilize a rotating spacecraft?

Tethered spacecrafts are systems of two or more bodies connected through long high-strength cables in a space environment. The dynamics and applications of these systems are considered in this study to explore new methods for passive spin stabilization. Since efforts for future deep space missions are currently under development, the management of resources that support human life and provide artificial gravity is a big concern. While other works have explored the use of active stabilization for tethered spacecrafts [4], the objective of this study is to achieve the same effective stabilization and reliability without the need to use propellants or power.

To prove that the distribution of water and air between elements of a tethered system is realistic, the fluid dynamics inside the conceptual spacecraft model is analysed. Relocating non-potable water alongside the spacecraft to balance the weight and therefore shift the center of mass, is an efficient technique for achieving the main goal and develop a new fluids management system for long-term space missions.

Another reason it's important to understand the behaviors of spinning, tethered systems, is because it's one of the principal keys to creating artificial gravity on long distance travel through deep space. This method uses the fundamentals of centripetal force, creating a "pulling" effect that simulates gravity inside the spacecraft. One of the scientists to explore this concept was American physicist, Gerard K. O'Neill, in his book "The High Frontier: Human Colonies in Space"[5].

His concept, colloquially known as the "O'Neill cylinder" involved two counter-rotating cylinders that would provide artificial gravity for a space settlement within the inside face. This model would work by rotating about 28 times an hour to simulate the standard Earth gravity and would have an angular velocity

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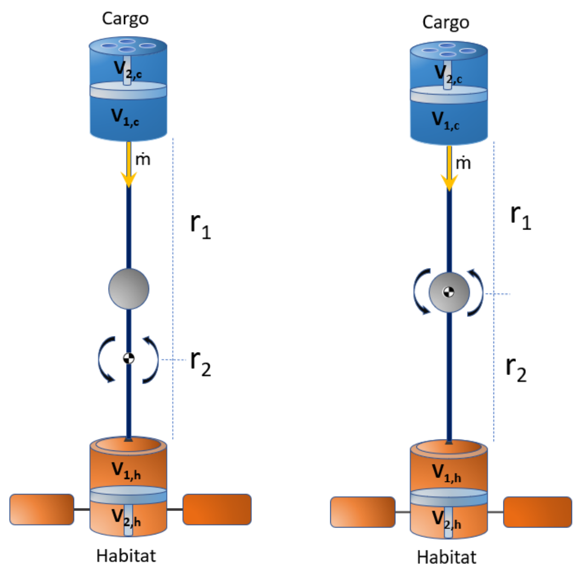
of 2.8 degrees per second. It is believed that at these speeds, the central axis of the cylinders would be a zero-gravity region which could be used for experimental or operational research development.

One of the concepts that could be furthered developed there is on-orbit manufacturing using variable gravity on tethered systems. The possibilities of manufacturing products on different gravity levels are still being explored but they have the potential to yield results that we solely can't get on Earth. As well, having the capability to do on-orbit manufacturing provides unique advantages for sustainable human exploration as we travel through deep space.

A concept model of a tethered spacecraft can be seen in Figure 1, where the shifted center of mass is exaggerated.



(a) Shifted Center of Mass (b) Corrected Center of Mass

Figure 1: Concept model of a tethered spacecraft

The conceptual extension of this system may be a annulus of fluid, a variation of which was explored for the purposes of attitude control by [6]. By exploring passive asymptotic stability of a bi-nodal spinning system, it can be extended to multiple nodes and then a continuum of time-varying mass. By exploring this parameter space, the implications to systems such as refuelers and manned spacecraft will be better understood.

DYNAMICS OF FLUIDS IN A ROTATING, TETHERED SPACECRAFT

The concept of tethered systems has the potential to open up new possibilities in space exploration [7]. However, efforts to understand the dynamics of a rotating, tethered spacecraft are still underway. In this paper, the behavior of the center of mass in relation to the distribution of fluids along the system are modeled using mathematical expressions.

In a spinning system, the acceleration experienced at any point along radius r, denoted as $\ddot{r}$, may be expressed as a function of angular speed, $\dot{\theta}$, or as a function of induced pressure in relation to mass m in relation to the surface area A as

$$\begin{aligned} \ddot{r} &= \frac{\dot{\theta}^2}{R} \\ \ddot{r} &= \frac{PA}{m} \end{aligned} \tag{1}$$

Consider a pressure vessel contained within one of two rotating elements (see Fig. 1) with an area perpendicular to both the axis of rotation and the acceleration vector. The induced pressure caused by a difference between two volumes at opposing ends of a tethered spacecraft, such as a habitation and cargo element, may be expressed as

$$P = \frac{m_1(t)\ddot{r}_1(t)}{A_1} - \frac{m_2(t)\ddot{r}_2(t)}{A_2} \tag{2}$$

We can substitute Eq. 1 in for acceleration where angular velocity for both is the same, yielding

$$P = \frac{m_1(t)\dot{\theta}^2}{R_1 A_1} - \frac{m_2(t)\dot{\theta}^2}{R_2 A_2} \tag{3}$$

$$P = \frac{m_1(t)(\dot{\theta}^2)}{R_1 A_1} - \frac{m_2(t)(\dot{\theta}^2)}{(R_T R_1)A_1} \tag{4}$$

$$P = \frac{m_1(t)\dot{\theta}^2}{R_1 A_1} + \frac{m_T\dot{\theta}^2}{R_T A_2} \tag{5}$$

We then define a body frame $\mathfrak{B}$ with an origin at the center of the propulsion element, which is also the desired center of mass. The true center of mass with respect to this body frame is derived from the formula for the center of mass of a multi-body system expressed as

$$r_{cm} = \frac{1}{m_T}\sum_{i=1}^{n} m_i r_i \tag{6}$$

where n is the number of bodies. For this simplified example, we assume that the change in center of mass is small, and thus consider only the two bodies: the habitation element and the cargo element, neglecting the central propulsion element. The resulting expression is

$$r_{cm/\mathfrak{B}} = \frac{1}{m_T}(m_1 r_1 - m_2 r_2) \tag{7}$$

However, since both mass m_T and the total distance r_T between the elements remain constant, we can rewrite this expression as

$$r_{cm/\mathfrak{B}} = \frac{1}{m_T}\left(m_1 r_1 - (m_T - m_1)(r_T - r_1)\right) = r_1 - r_T + \frac{r_T m_1}{m_T} \tag{8}$$

However, the center of mass is also located at the sum of r_1 and r_2, assuming that they are along the same axis along the center of mass frame. Plug this into equation 8 to yield

$$r_{cm/\mathfrak{B}} = r_1 + r_2 = r_1 - r_T + \frac{r_T m_1(t)}{m_T} \tag{9}$$

or, simplified, as

$$r_2 = \frac{r_T m_1(t)}{m_T} - r_T \tag{10}$$

r_2 may then be used in 3 to yield

$$P = \frac{m_1(t)\dot{\theta}^2}{r_1 A_1} - \frac{m_2(t)\dot{\theta}^2}{(\frac{r_T}{m_T}(m_1(t) - r_T))A_2} = \frac{m_1(t)\dot{\theta}^2}{r_1(t)A_1} + \frac{m_T\dot{\theta}^2}{r_T A_2} \tag{11}$$

Then, the time derivative of this function is taken to determine the change in pressure with respect to time, $\dot{P}$. However, we assume that $\dot{\theta}, A_1, A_2, m_T$, and r_T are all constant, yielding

$$\dot{P} = \frac{\dot{m_1}(t)\dot{\theta}^2}{r_1 A_1} - \frac{m_1(t)\dot{\theta}^2\dot{r_1}}{r_1^2 A_1} \tag{12}$$

Next, the time derivative of r is expressed and the chain rule is applied as

$$\dot{r} = \frac{\mathrm{d}r}{\mathrm{d}m_1}\frac{\mathrm{d}m_1}{\mathrm{d}t} = \frac{dr}{dt}\dot{m} \tag{13}$$

where $\frac{\mathrm{d}m}{\mathrm{d}t} = \dot{m}$ and $\frac{\mathrm{d}r}{\mathrm{d}m_1} = \frac{\mathrm{d}r_{cm}}{\mathrm{d}m_1}$. The right side of Eq.8 is used to yield

$$\frac{\mathrm{d}r_{cm}}{\mathrm{d}m_1} = \frac{r_T \dot{m}_1}{m_T} \tag{14}$$

We then plug this into Eq. 13 and have

$$\dot{r} = \frac{r_T \dot{m}_1}{m_T}\dot{m} \tag{15}$$

The expression for the $r_1(t)$ can then be expressed as

$$r(t) = r_{1,o} + \dot{r_1}\mathrm{d}t \tag{16}$$

However, if we assume our initial state is at the desired position of $r_1 = r_2$, then $r_1 = \frac{1}{2}r_T$. We can plug this in as well as the derived equation for $\dot{r_1}$ to have

$$r_1(t) = \frac{r_T}{2} + \frac{r_T \dot{m}}{m_T \dot{m} t} \tag{17}$$

Finally, the pressure can be expressed as an explicit function of time by substituting $m_1 = m_{1,o} + \dot{m}\mathrm{d}t$ and $r_1(t)$ with the result from equation 17:

$$P(t) = (m_{1,0} + \dot{m}t)\frac{\theta}{r_1 A_1} \tag{18}$$

By gaining an understanding of how this pressure changes over time, we can design a system around this changing pressure and refine our assumptions over time to create a passively stable dynamical system, such that any gravitational jerk is negative, resulting in asymptotic stability.

CASE STUDY

Figure 2 shows the analysis of motion of a tethered spacecraft when the center of mass is aligned with the geometric center of the system. This allows for the verification of our mathematical analysis shown before, simulating the rotation of the elements using their inertial frame and their rotating frame as references. The inertial frame illustrates the rotation of the system as a whole while it travels through space, while the rotating frame shows the wobble of the spinning axis as the center of mass slightly shifts.

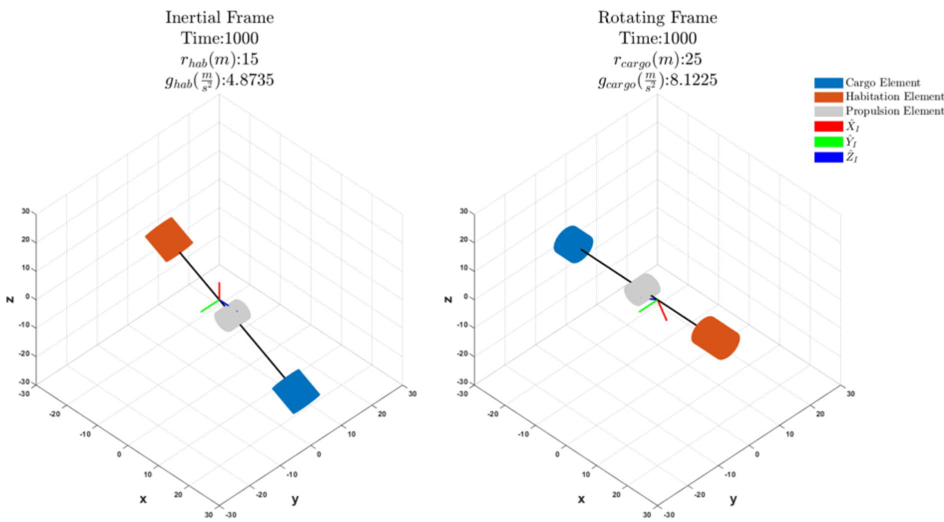


Figure 2: The result of about 16 minutes of simulation. As mass flows from the cargo element to the habitation element, the displacement of mass results in a significant change in perceived gravity.

EXPECTED RESULTS

With preliminary modeling and formalism complete, the remaining work on this project will focus on the stability analysis for various configurations. Notionally, this work is extensible to a continuum of nodes that would eventually form an annulus of fluid that could act as ballast or an attitude control system for manned spacecraft or on-orbit refueling, which is of specific interest for both Artemis program and satellite servicing. This work would demonstrate passive and active control for spacecraft with dynamically moving fluid and cargo within a pressurized cargo or habitable volume.

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